

Variation of fundamental constants

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Theories unifying gravity with other interactions suggest temporal and spatial variation of the fundamental "constants" in expanding Universe. The spatial variation can explain a fine tuning of the fundamental constants which allows humans (and any life) to appear. We appeared in the area of the Universe where the values of the fundamental constants are consistent with our existence.

We present a review of recent works devoted to the variation of the fine structure constant α , strong interaction and fundamental masses. There are some hints for the variation in quasar absorption spectra, Big Bang nucleosynthesis, and Oklo natural nuclear reactor data.

A very promising method to search for the variation of the fundamental constants consists in comparison of different atomic clocks. Huge enhancement of the variation effects happens in transition between accidentally degenerate atomic and molecular energy levels. A new idea is to build a "nuclear" clock based on the ultraviolet transition between very low excited state and ground state in Thorium nucleus. This may allow to improve sensitivity to the variation up to 10 orders of magnitude!

Huge enhancement of the variation effects is also possible in cold atomic and molecular collisions near Feshbach resonance.

I. INTRODUCTION

The possible variation of the fundamental constants of nature is currently a very popular research topic. Theories unifying gravity and other interactions suggest the possibility of spatial and temporal variation of physical "constants" in the Universe (see, e.g. [1, 2]). Current interest is high because in superstring theories – which have additional dimensions compactified on tiny scales – any variation of the size of the extra dimensions results in changes in the 3-dimensional coupling constants. At present no mechanism for keeping the spatial scale static has been found (for example, our three "large" spatial dimensions increase in size). Moreover, there exists a mechanism for making all coupling constants and masses of elementary particles both space and time dependent, and influenced by local circumstances (see e.g. review [2]). The variation of coupling constants can be non-monotonic (for example, damped oscillations).

Recent observations have produced several hints for the variation of the fine structure constant, $\alpha = e^2/\hbar c$, strength constant of the strong interaction and masses in Big Bang nucleosynthesis, quasar absorption spectra and Oklo natural nuclear reactor data (see e.g. [3, 4, 5, 6]). However, a majority of publications report only limits on possible variations (see e.g. reviews [2, 7]). A very sensitive method to study the variation in a laboratory consists of the comparison of different optical and microwave atomic clocks (see recent measurements in [8, 9, 10, 11, 12, 13, 14]). Huge enhancement of the relative variation effects can be obtained in transition between the almost degenerate levels in atoms [15, 16, 17, 18], molecules [19] and nuclei [20].

II. OPTICAL SPECTRA

A. Comparison of quasar absorption spectra with laboratory spectra

To perform measurements of α variation by comparison of cosmic and laboratory optical spectra we developed a new approach [15, 21] which improves the sensitivity to a variation of α by more than an order of magnitude. The relative value of any relativistic corrections to atomic transition frequencies is proportional to α^2 . These corrections can exceed the fine structure interval between the excited levels by an order of magnitude (for example, an s -wave electron does not have the spin-orbit splitting but it has the maximal relativistic correction to energy). The relativistic corrections vary very strongly from atom to atom and can have opposite signs in different transitions (for example, in s - p and d - p transitions). Thus, any variation of α could be revealed by comparing different transitions in different atoms in cosmic and laboratory spectra.

This method provides an order of magnitude precision gain compared to measurements of the fine structure interval. Relativistic many-body calculations are used to reveal the dependence of atomic frequencies on α for a range of atomic species observed in quasar absorption spectra [15, 16, 21, 22]. It is convenient to present results for the transition frequencies as functions of α^2 in the form

$$\omega = \omega_0 + qx, \quad (1)$$

where $x = (\frac{\alpha}{\alpha_0})^2 - 1 \approx \frac{2\delta\alpha}{\alpha}$ and ω_0 is a laboratory frequency of a particular transition. We stress that the second term contributes only if α deviates from the laboratory value α_0 . We performed accurate many-body calculations of the coefficients q for all transitions of astro-

physical interest (strong E1 transtions from the ground state) in Mg, Mg II, Fe II, Cr II, Ni II, Al II, Al III, Si II, and Zn II. It is very important that this set of transtions contains three large classes : positive shifters (large positive coefficients $q > 1000 \text{ cm}^{-1}$), negative shifters (large negative coefficients $q < -1000 \text{ cm}^{-1}$) and anchor lines with small values of q . This gives us an excellent control of systematic errors since systematic effects do not “know” about sign and magnitude of q . Comparison of cosmic frequencies ω and laboratory frequencies ω_0 allows us to measure $\frac{\delta\alpha}{\alpha}$.

Three independent samples of data contaning 143 absorption systems spread over red shift range $0.2 < z < 4.2$. The fit of the data gives [3] is $\frac{\delta\alpha}{\alpha} = (-0.543 \pm 0.116) \times 10^{-5}$. If one assumes the linear dependence of α on time, the fit of the data gives $d \ln \alpha / dt = (6.40 \pm 1.35) \times 10^{-16}$ per year (over time interval about 12 billion years). A very extensive search for possible systematic errors has shown that known systematic effects can not explain the result (It is still not completely excluded that the effect may be imitated by a large change of abundances of isotopes during last 10 billion years. We have checked that different isotopic abundances for any single element can not imitate the observed effect. It may be an improbable “conspiracy” of several elements).

Recently our method and calculations [15, 16, 21, 22] were used by two other groups [23]. However, they have not detected any variation of α . Most probably, the difference is explained by some undiscovered systematic effects. However, another explanation is not excluded. These results of [3] are based on the data from the Keck telescope which is located in the Northen hemisphere (Hawaii). The results of [23] are based on the data from the different telescope (VLT) located in the Southern hemisphere (Chile). Therefore, the difference in the results may be explained by the spatial variation of α .

Using opportunity I would like to ask for new, more accurate laboratory measurements of UV transition frequencies which have been observed in the quasar absorption spectra. The “shopping list” is presented in [24]. We also need the laboratory measurements of isotopic shifts - see [24]. We have performed very complicated calculations of these isotopic shifts [25]. However, the accuracy of these calculations in atoms and ions with open d-shell (like Fe II, Ni II, Cr II, Mn II, Ti II) may be very low. The measurements for at list few lines are needed to test these calculations. These measurements would be very important for a study of evolution of isotope abundances in the Universe, to exclude the systematic effects in the search for α variation and to test models of nuclear reactions in stars and supernovi.

B. Optical cloks

Optical clocks also include transitions which have positive, negative or small constributions of the relativistic corrections to frequencies. We used the same methods of

the relativistic many-body calculations to calculate the dependence on α [15, 16, 26]. The coefficients q for optical clock transitions may be substantially larger than in cosmic transitions since the clock transitions are often in heavy atoms (Hg II, Yb II, Yb III, etc.) while cosmic spectra contain mostly light atoms lines ($Z < 33$). The relativistic effects are proportional to $Z^2 \alpha^2$.

III. ENHANCED EFFECTS OF α VARIATION IN ATOMS

An enhancement of the relative effect of α variation can be obtained in transition between the almost degenerate levels in Dy atom [15, 16]. These levels move in opposite directions if α varies. The relative variation may be presented as $\delta\omega/\omega = K\delta\alpha/\alpha$ where the coefficient K exceeds 10^8 . Specific values of $K = 2q/\omega$ are different for different hyperfine components and isotopes which have different ω ; $q = 30,000 \text{ cm}^{-1}$, $\omega \sim 10^{-4} \text{ cm}^{-1}$. An experiment is currently underway to place limits on α variation using this transition [18]. Unfortunately, one of the levels has quite a large linewidth and this limits the accuracy.

Several enhanced effects of α variation in atoms have been calculated in [17].

IV. ENHANCED EFFECTS OF α VARIATION IN MOLECULES

The relative effect of α variation in microwave transitions between very close and narrow rotational-hyperfine levels may be enhanced 2-3 orders of magnitude in diatomic molecules with unpaired electrons like LaS, LaO, LuS, LuO, YbF and similar molecular ions [19]. The enhancement is a result of cancellation between the hyperfine and rotational intervals; $\delta\omega/\omega = K\delta\alpha/\alpha$ where the coefficients K are between 10 and 1000.

V. VARIATION OF THE STRONG INTERACTION

The hypothetical unification of all interactions implies that a variation in α should be accompanied by a variation of the strong interaction strength and the fundamental masses. For example, the grand unification model discussed in Ref. [1] predicts the quantum chromodynamics (QCD) scale Λ_{QCD} (defined as the position of the Landau pole in the logarithm for the running strong coupling constant, $\alpha_s(r) \sim 1/\ln(\Lambda_{QCD}r/\hbar c)$) is modified as $\delta\Lambda_{QCD}/\Lambda_{QCD} \approx 34 \delta\alpha/\alpha$. The variations of quark mass m_q and electron masses m_e (related to variation of the Higgs vaccuum field which generates fundamental masses) in this model are given by $\delta m/m \sim 70 \delta\alpha/\alpha$, giving an estimate of the variation for the dimensionless

ratio

$$\frac{\delta(m/\Lambda_{QCD})}{(m/\Lambda_{QCD})} \sim 35 \frac{\delta\alpha}{\alpha} \quad (2)$$

The coefficient here is model dependent but large values are generic for grand unification models in which modifications come from high energy scales; they appear because the running strong-coupling constant and Higgs constants (related to mass) run faster than α . If these models are correct, the variation in electron or quark masses and the strong interaction scale may be easier to detect than a variation in α . One can only measure the variation of dimensionless quantities. The variation of m_q/Λ_{QCD} can be extracted from consideration of Big Bang nucleosynthesis, quasar absorption spectra and the Oklo natural nuclear reactor, which was active about 1.8 billion years ago [27]. There are some hints for the variation in Big Bang Nucleosynthesis ($\sim 10^{-3}$ [4]) and Oklo ($\sim 10^{-9}$ [5]) data. The results for the variation have small statistical errors (4 standard deviations from zero for BBN and 11 standard deviations for Oklo). However, it may be hard to prove that there are no other explanations for the deviations since both phenomena are very complicated.

The proton mass is proportional to Λ_{QCD} ($M_p \sim 3\Lambda_{QCD}$), therefore, the measurements of the variation of the electron-to-proton mass ratio $\mu = m_e/M_p$ is equivalent to the measurements of the variation of $X_e = m_e/\Lambda_{QCD}$. Two new results have been obtained recently using quasar absorption spectra. In our paper [28] the variation of the ratio of the hydrogen hyperfine frequency to optical frequencies in ions have been measured. The result is consistent with no variation of $X_e = m_e/\Lambda_{QCD}$. However, in the most recent paper [6] the variation was detected at the level of 4 standard deviations: $\frac{\delta X_e}{X_e} = \frac{\delta\mu}{\mu} = (-2.4 \pm 0.6) \times 10^{-5}$. This result is based on the hydrogen molecule spectra. Note, however, that the difference between the zero result of [28] and non-zero result of [6] may be explained by a space-time variation of X_e . The variation of X_e in [6] is substantially larger than the variation of α measured in [3, 23]. This may be considered as an argument in favour of Grand Unification theories of the variation [1].

VI. MICROWAVE CLOCKS

Karshenboim [29] has pointed out that measurements of ratios of hyperfine structure intervals in different atoms are sensitive to variations in nuclear magnetic moments. However, the magnetic moments are not the fundamental parameters and can not be directly compared with any theory of the variations. Atomic and nuclear calculations are needed for the interpretation of the measurements. We have performed both atomic calculations of α dependence [15, 16, 26] and nuclear calculations of $X_q = m_q/\Lambda_{QCD}$ dependence [30] for all microwave transitions of current experimental interest including hyper-

fine transitions in ^{133}Cs , ^{87}Rb , $^{171}\text{Yb}^+$, $^{199}\text{Hg}^+$, ^{111}Cd , ^{129}Xe , ^{139}La , ^1H , ^2H and ^3He . The results for the dependence of the transition frequencies on variation of α , $X_e = m_e/\Lambda_{QCD}$ and $X_q = m_q/\Lambda_{QCD}$ are presented in Ref.[30] (see the final results in the Table IV of Ref.[30]). Also, one can find there experimental limits on these variations which follow from the recent measurements. The accuracy is approaching 10^{-15} per year. This may be compared to the sensitivity $\sim 10^{-5} - 10^{-6}$ per 10^{10} years obtained using the quasar absorption spectra.

VII. ENHANCED EFFECT OF VARIATION OF α AND STRONG INTERACTION IN UV TRANSITION OF ^{229}Th NUCLEUS (NUCLEAR CLOCK)

A very narrow level (3.5 ± 1) eV above the ground state exists in ^{229}Th nucleus [31] (in [32] the energy is (5.5 ± 1) eV). The position of this level was determined from the energy differences of many high-energy γ -transitions (between 25 and 320 KeV) to the ground and excited states. The subtraction produces the large uncertainty in the position of the 3.5 eV excited state. The width of this level is estimated to be about 10^{-4} Hz [33]. This would explain why it is so hard to find the direct radiation in this very weak transition. The direct measurements have only given experimental limits on the width and energy of this transition (see e.g. [34]). A detailed discussion of the measurements (including several unconfirmed claims of the detection of the direct radiation) is presented in Ref.[33]. However, the search for the direct radiation continues [35].

The ^{229}Th transition is very narrow and can be investigated with laser spectroscopy. This makes ^{229}Th a possible reference for an optical clock of very high accuracy, and opens a new possibility for a laboratory search for the variation of the fundamental constants [36].

As it is shown in Ref. [20] there is an additional very important advantage. The relative effects of variation of α and m_q/Λ_{QCD} are enhanced by 5-6 orders of magnitude. The estimate for the relative variation of the ^{229}Th transition frequency is

$$\frac{\delta\omega}{\omega} \approx 10^5 \left(4 \frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10 \frac{\delta X_s}{X_s} \right) \frac{3.5 \text{ eV}}{\omega} \quad (3)$$

where $X_q = m_q/\Lambda_{QCD}$, $X_s = m_s/\Lambda_{QCD}$, $m_q = (m_u + m_d)/2$ and m_s is the strange quark mass. Therefore, the Th experiment would have the potential of improving the sensitivity to temporal variation of the fundamental constants by many orders of magnitude.

Note that there are other narrow low-energy levels in nuclei, e.g. 76 eV level in ^{235}U with the 26.6 minutes lifetime (see e.g.[36]). One may expect a similar enhancement there. Unfortunately, this level can not be reached with usual lasers. In principle, it may be investigated using a free-electron laser or synchrotron radiation.

However, the accuracy of the frequency measurements is much lower in this case.

VIII. ENHANCEMENT OF VARIATION OF FUNDAMENTAL CONSTANTS IN ULTRACOLD ATOM AND MOLECULE SYSTEMS NEAR FESHBACH RESONANCES

Scattering length A , which can be measured in Bose-Einstein condensate and Feshbach molecule experiments, is extremely sensitive to the variation of the electron-to-proton mass ratio $\mu = m_e/m_p$ or $X_e = m_e/\Lambda_{QCD}$ [37].

$$\frac{\delta A}{A} = K \frac{\delta \mu}{\mu} = K \frac{\delta X_e}{X_e}, \quad (4)$$

where K is the enhancement factor. For example, for Cs-Cs collisions we obtained $K \sim 400$. With the Feshbach resonance, however, one is given the flexibility to adjust position of the resonance using external fields. Near a narrow magnetic or an optical Feshbach resonance the enhancement factor K may be increased by many orders of magnitude.

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